CIS 5930 Advanced Topics in Data Management

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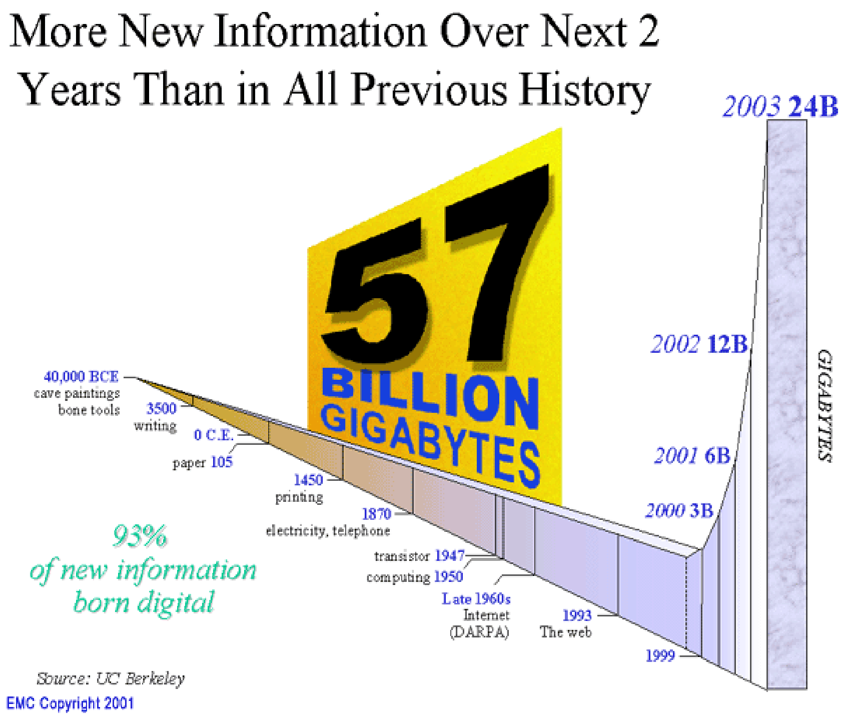
(Many slides were made available by Ke Yi)

Massive Data

- Massive datasets are being collected everywhere
- Storage management software is billion-$ industry

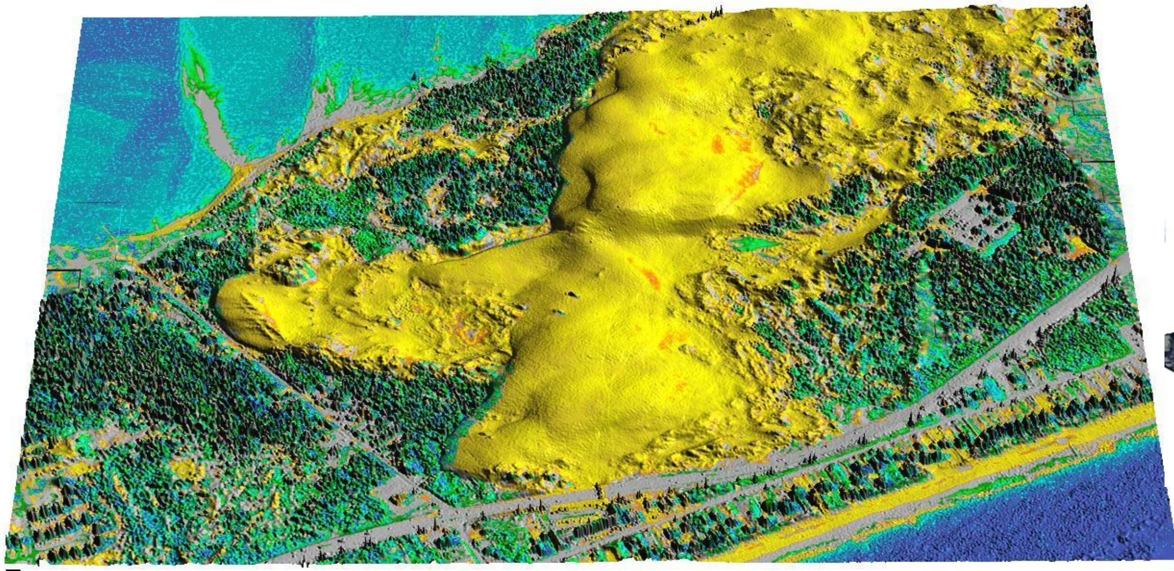


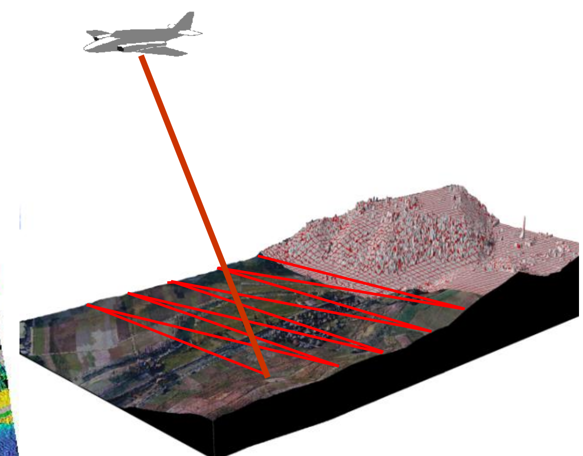
Examples (2002):

- Phone: AT&T 20TB phone call database, wireless tracking
- Consumer: WalMart 70TB database, buying patterns
- WEB: Web crawl of 200M pages and 2000M links, Akamai stores 7 billion clicks per day
- Geography: NASA satellites generate 1.2TB per day

Example: LIDAR Terrain Data

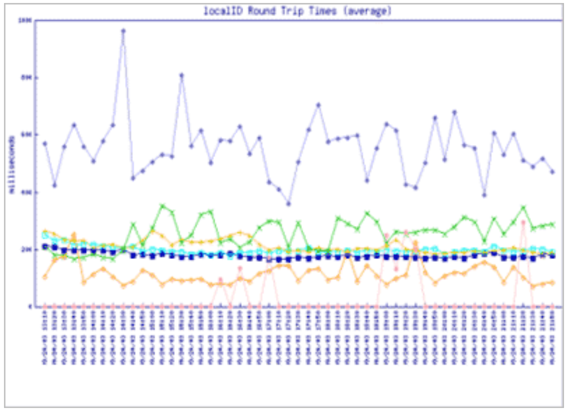
- Massive (irregular) point sets (1-10m resolution)
  - Becoming relatively cheap and easy to collect
- Appalachian Mountains between 50GB and 5TB
- Exceeds memory limit and needs to be stored on disk





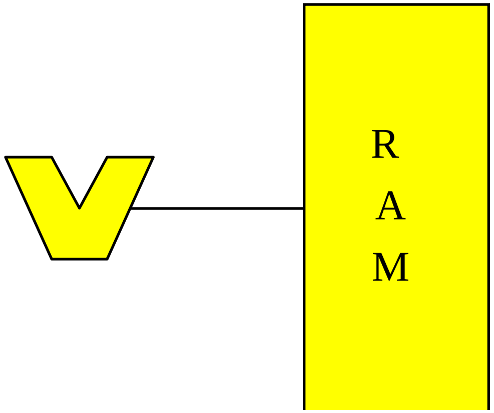
Example: Network Flow Data

- AT&T IP backbone generates 500 GB per day
- Gigascope: A data stream management system
  - Compute certain statistics



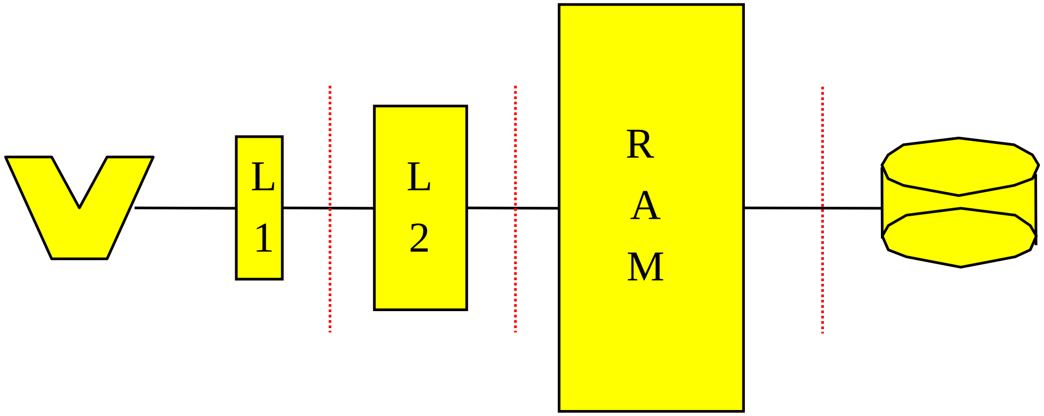
- Can we do computation without storing the data?

Random Access Machine Model



- Standard theoretical model of computation:
  - Infinite memory
  - Uniform access cost
- Simple model crucial for success of computer industry

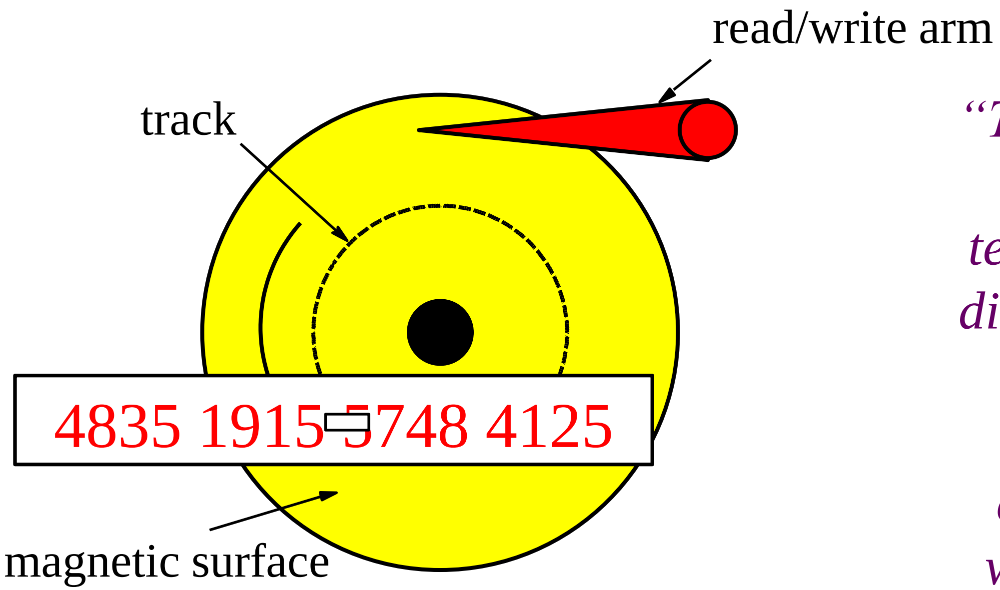
Hierarchical Memory



- Modern machines have complicated memory hierarchy
  - Levels get larger and slower further away from CPU
  - Data moved between levels using large blocks

Slow I/O

- Disk access is 10^6 times slower than main memory access



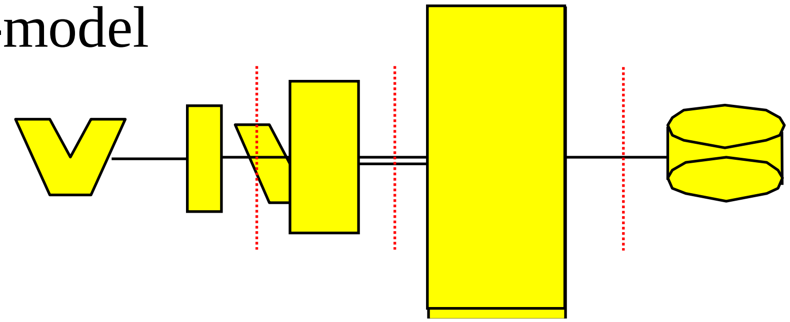
"The difference in speed between modern CPU and disk technologies is analogous to the difference in speed in sharpening a pencil using a sharpener on one's desk or by taking an airplane to the other side of the world and using a sharpener on someone else's desk." (D. Comer)

– Disk systems try to amortize large access time transferring large contiguous blocks of data (8-16Kbytes)

– Important to store/access data to take advantage of blocks (locality)

Scalability Problems

- Most programs developed in RAM-model
  - Run on large datasets because OS moves blocks as needed



- Moderns OS utilizes sophisticated paging and prefetching strategies
  - But if program makes scattered accesses even good OS cannot take advantage of block access

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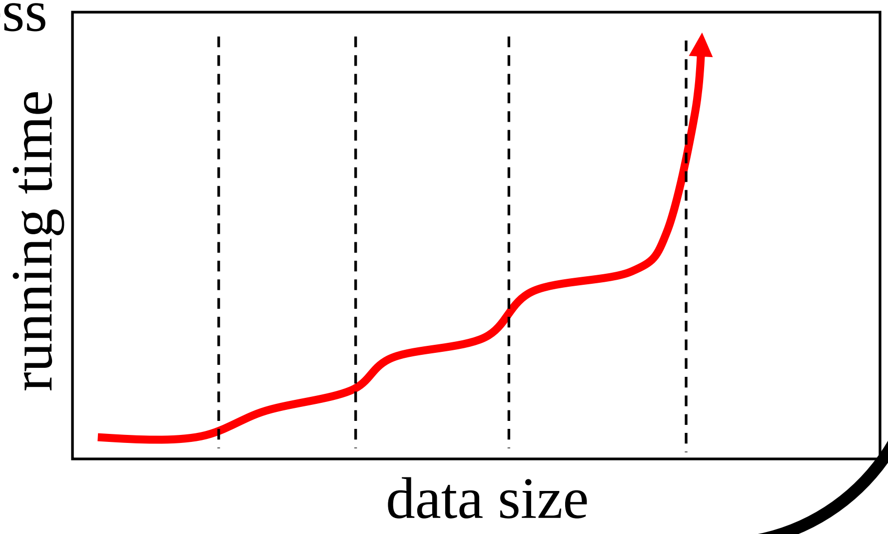
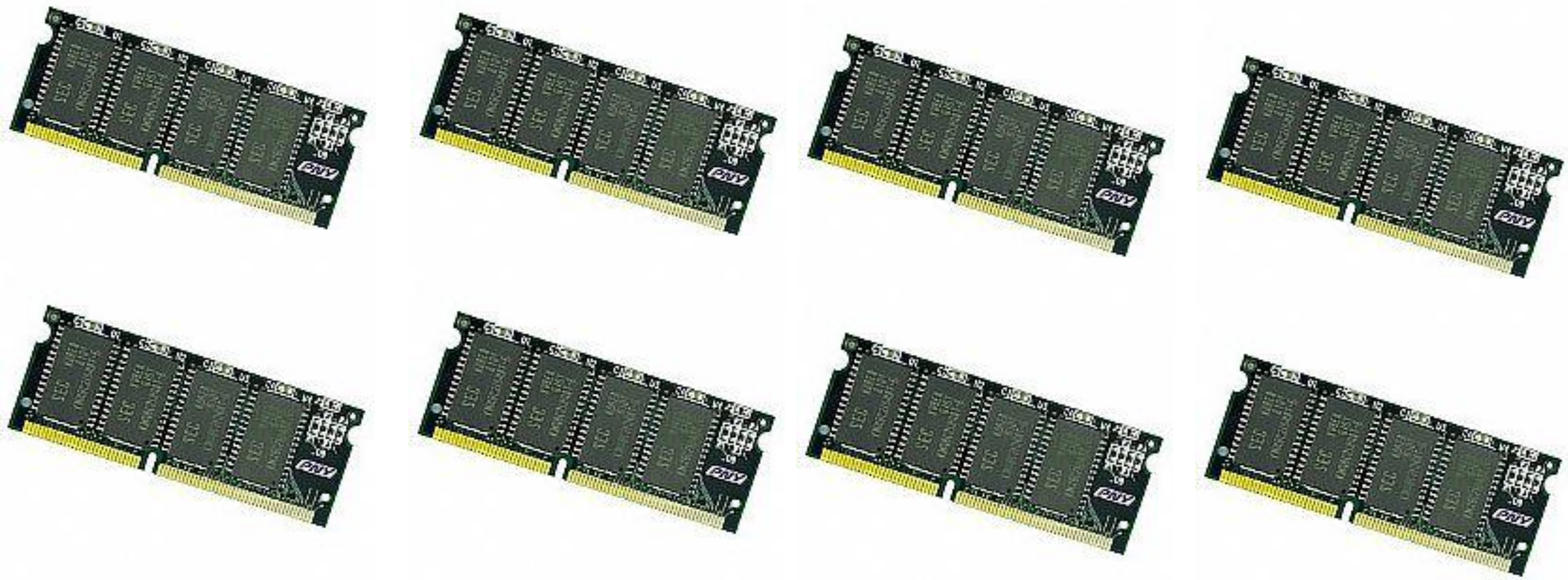
Scalability problems!



Solution 1: Buy More Memory



- Expensive
- (Probably) not scalable
  - Growth rate of data is higher than the growth of memory

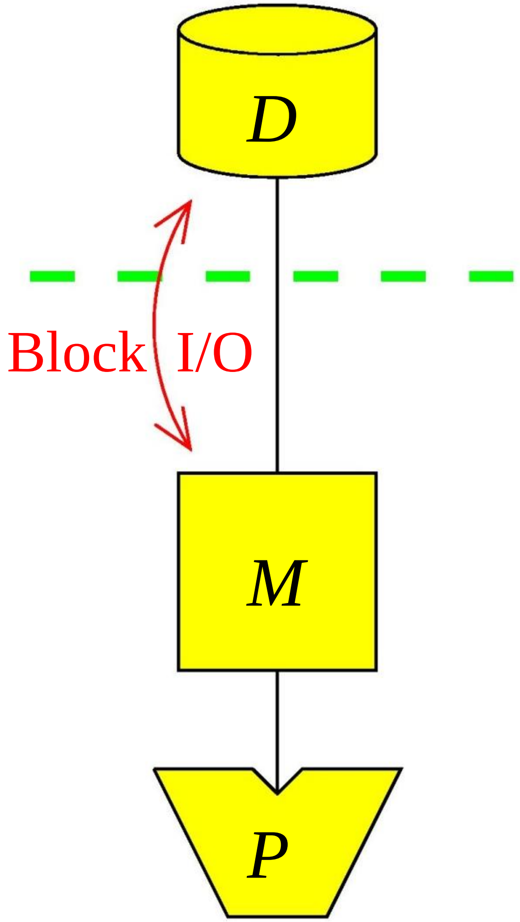
Solution 2: Cheat! (by random sampling)

- Provide approximate solution for some problems
  - average, frequency of an element, etc.
- What if we want the exact result?
- Many problems can't be solved by sampling
  - maximum, and all problems mentioned later

Solution 3: Using the Right Computation Model

- External Memory Model
- Streaming Model
- Uncertain Data Model

External Memory Model



N = # of items in the problem instance

B = # of items per disk block

M = # of items that fit in main memory

T = # of items in output

I/O: Move block between memory and disk

We assume (for convenience) that $M > B^2$

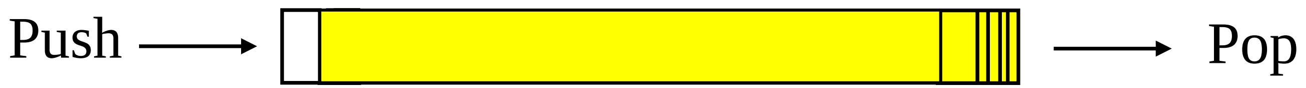
Fundamental Bounds

	Internal	External
• Scanning:	N	$\frac{N}{B}$
• Sorting:	$N \log N$	$\frac{N}{B} \log_{M/B} \frac{N}{B}$
• Permuting	N	$\min\{N, \frac{N}{B} \log_{M/B} \frac{N}{B}\}$
• Searching:	$\log_2 N$	$\log_B N$

- Note:
  - Linear I/O: $O(N/B)$
  - Permuting not linear
  - Permuting and sorting bounds are equal in all practical cases
  - B factor VERY important: $\frac{N}{B} < \frac{N}{B} \log_{M/B} \frac{N}{B} << N$
  - Cannot sort optimally with search tree

Queues and Stacks

- Queue:
  - Maintain push and pop blocks in main memory



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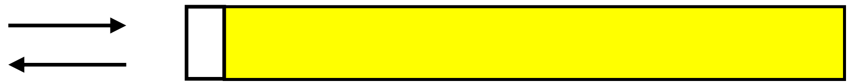
$O(1/B)$ Push/Pop operations

- Stack:
  - Maintain push/pop block in main memory



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$O(1/B)$ Push/Pop operations

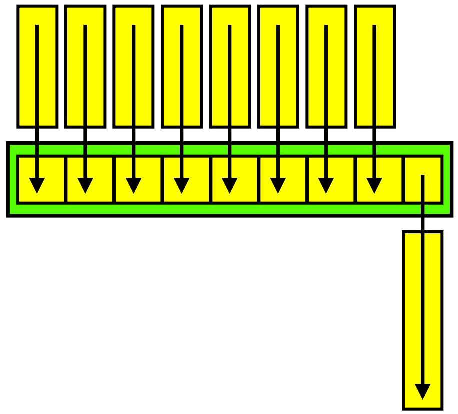
Puzzle #1: Majority Counting

b	a	e	c	a	d	a	a	d	a	a	e	a	b	a	a	f	a	g	b

- A huge file of characters stored on disk
- Question: Is there a character that appears > 50% of the time
- Solution 1: sort + scan
  – A few passes ($O(\log_{M/B} N)$): will come to it later
- Solution 2: divide-and-conquer
  – Load a chunk in to memory: N/M chunks
  – Count them, return majority
  – The overall majority must be the majority in >50% chunks
  – Iterate until $< M$
  – Very few passes ($O(\log_M N)$), geometrically decreasing
- Solution 3: O(1) memory, 2 passes (answer to be posted later)

Sorting

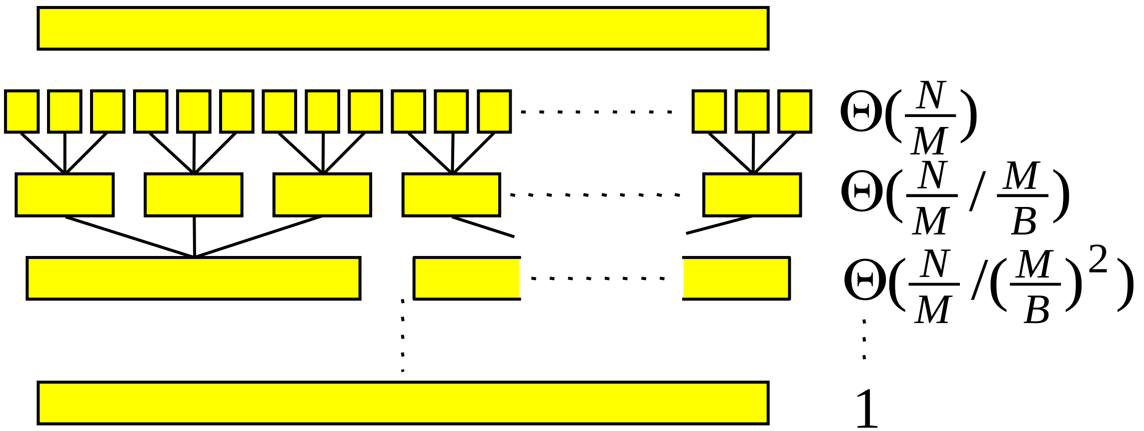
- $<M/B$ sorted lists (queues) can be merged in $O(N/B)$ I/Os



M/B blocks in main memory

Sorting

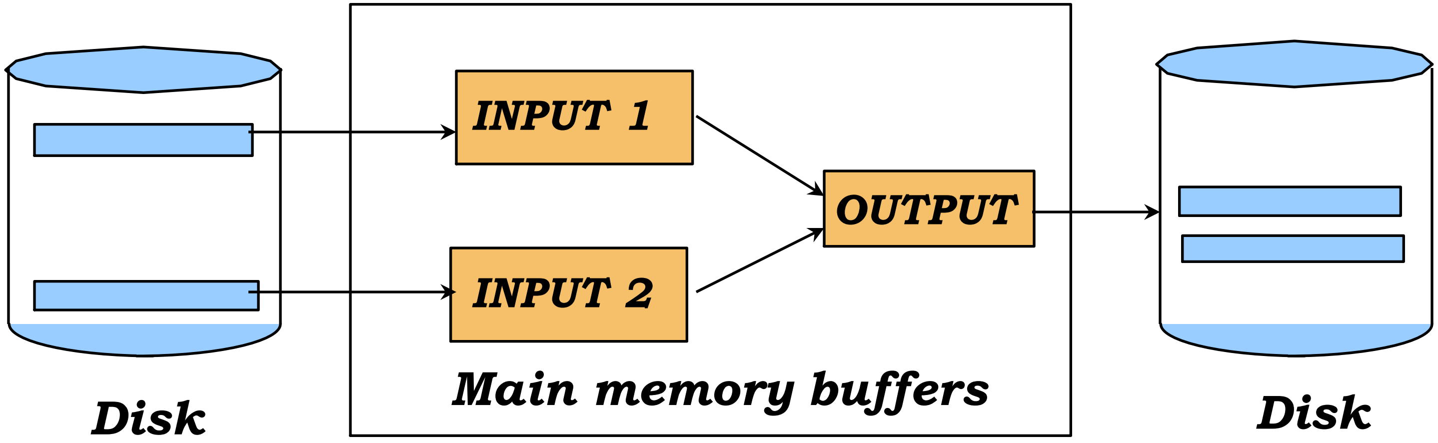
- Merge sort:
  - Create N/M memory sized sorted lists
  - Repeatedly merge lists together $\Theta(M/B)$ at a time



$\Rightarrow O(\log_{M/B} \frac{N}{M})$ phases using $O(N/B)$ I/Os each $\Rightarrow O(\frac{N}{B} \log_{M/B} \frac{N}{B})$ I/Os

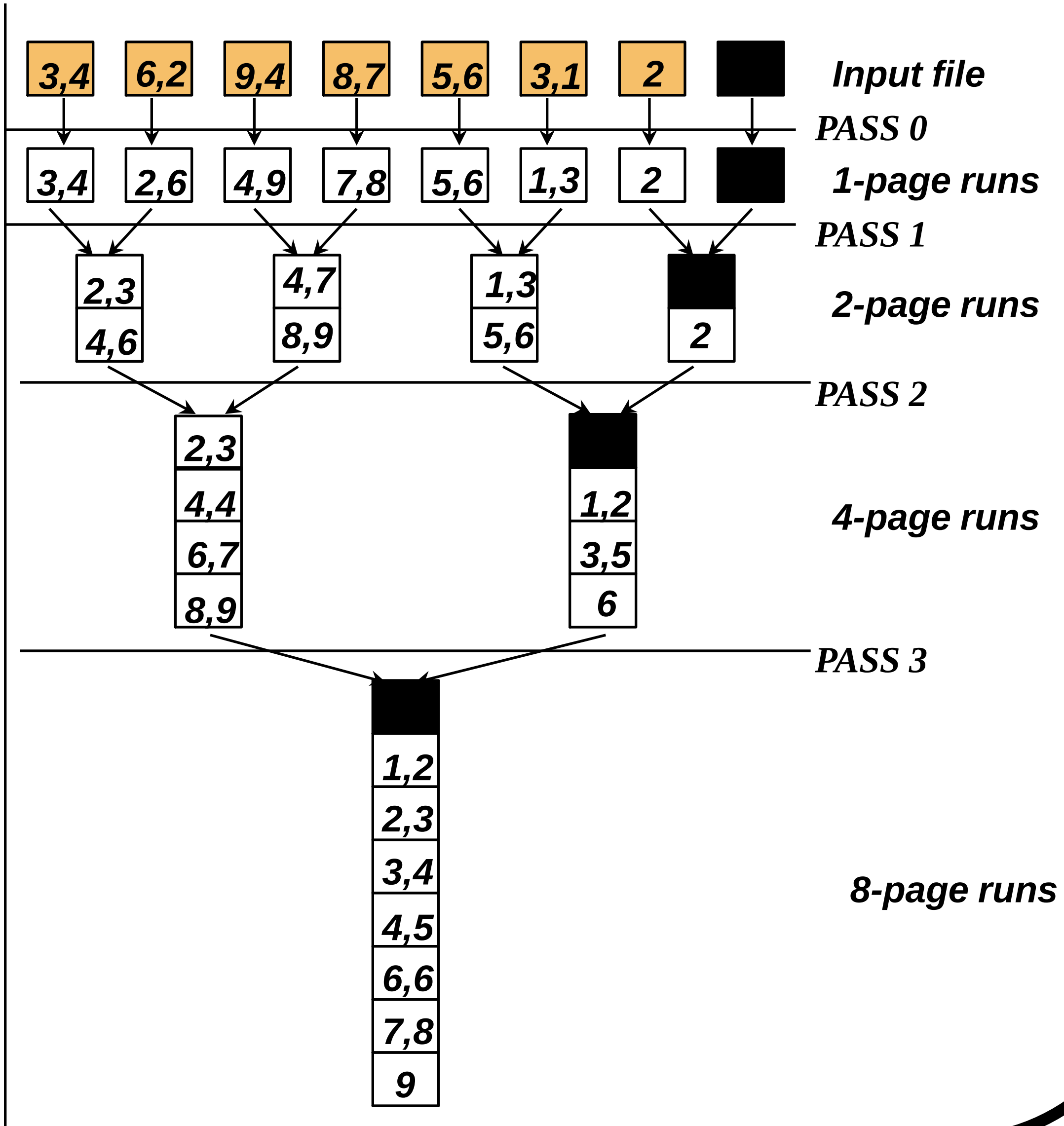
2-Way Sort: Requires 3 Buffers

- Phase 1: PREPARE.
  - Read a page, sort it, write it.
  - only one buffer page is used
- Phase 2, 3, …, etc.: MERGE:
  - three buffer pages used.



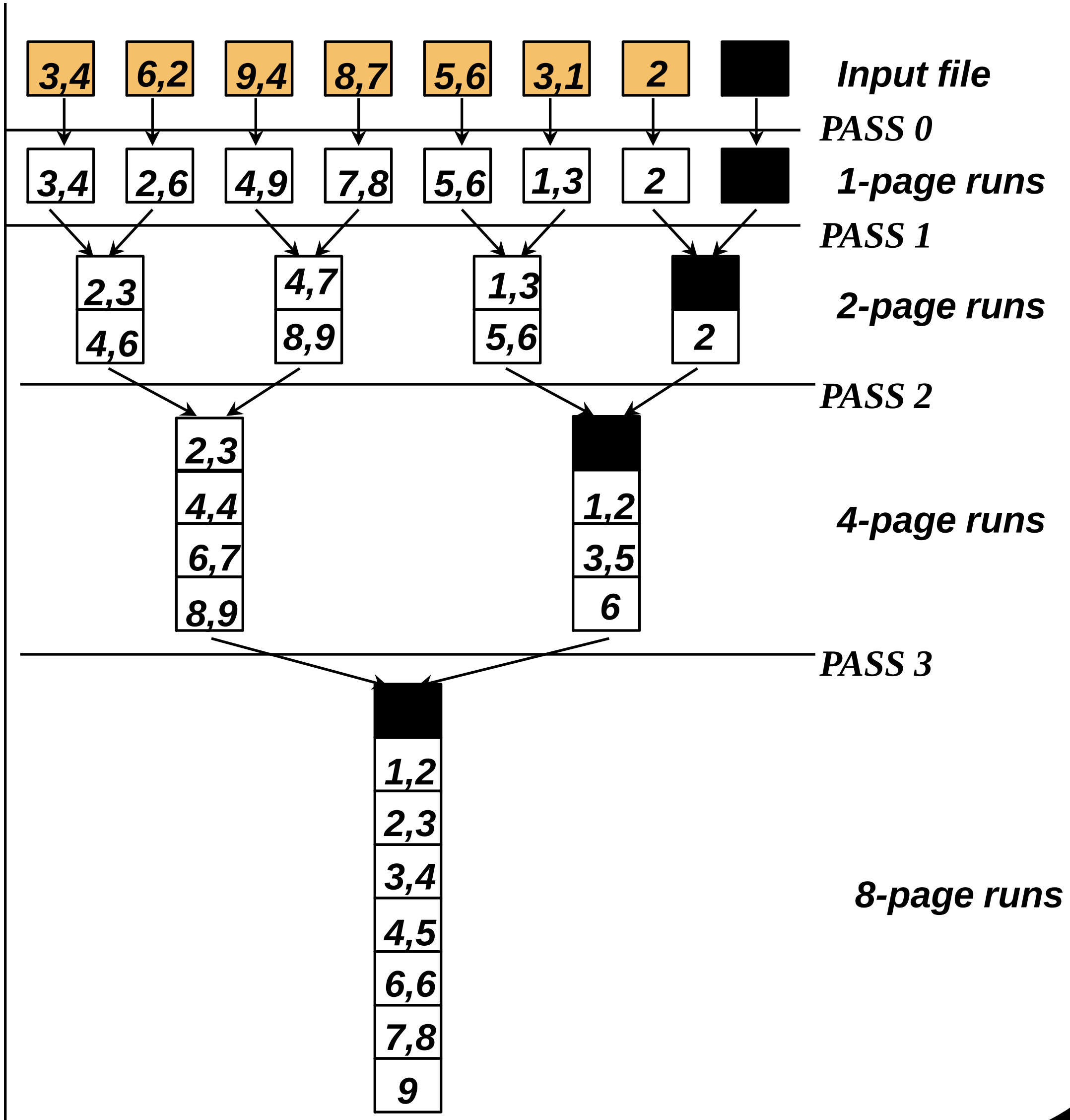
Two-Way External Merge Sort

- *<u>Idea:</u> Divide and conquer:* sort subfiles and merge into larger sorts



Two-Way External Merge Sort

- Costs for pass : all pages
- # of passes : height of tree
- Total cost : product of above



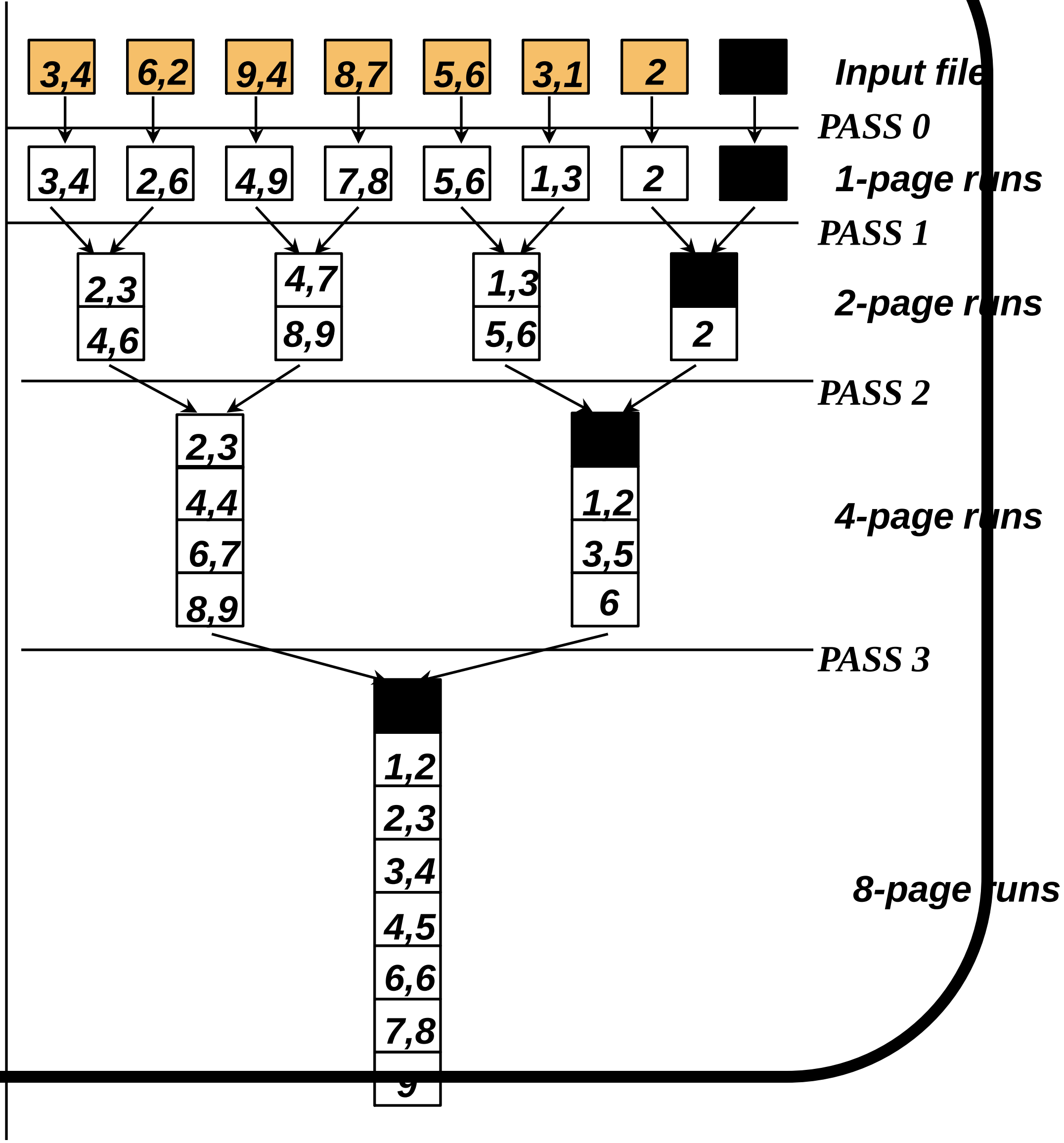
Two-Way External Merge Sort

- Each pass we read + write each page in file.
- N/B pages in file => 2N/B
- Number of passes

$$= \lceil \log_2 N / B \rceil + 1$$

- So total cost is:

$$2N / B\left(\lceil \log_2 N / B \rceil + 1\right)$$

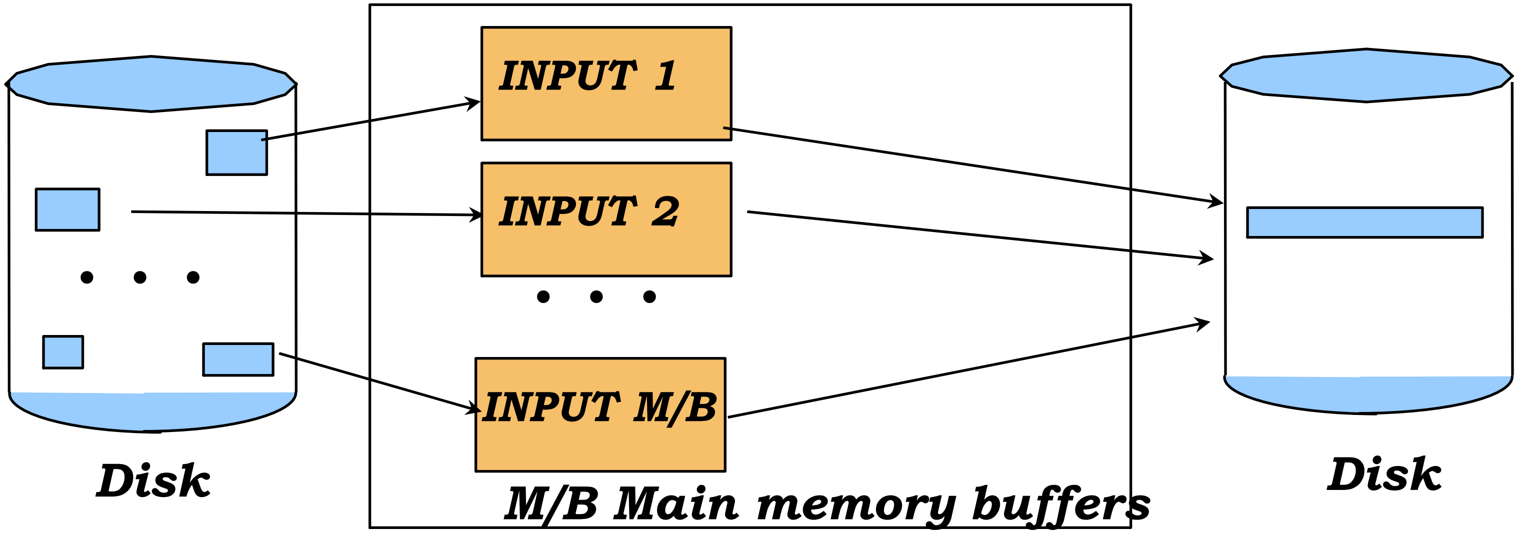


External Merge Sort

- What if we had more buffer pages?
- How do we utilize them wisely ?

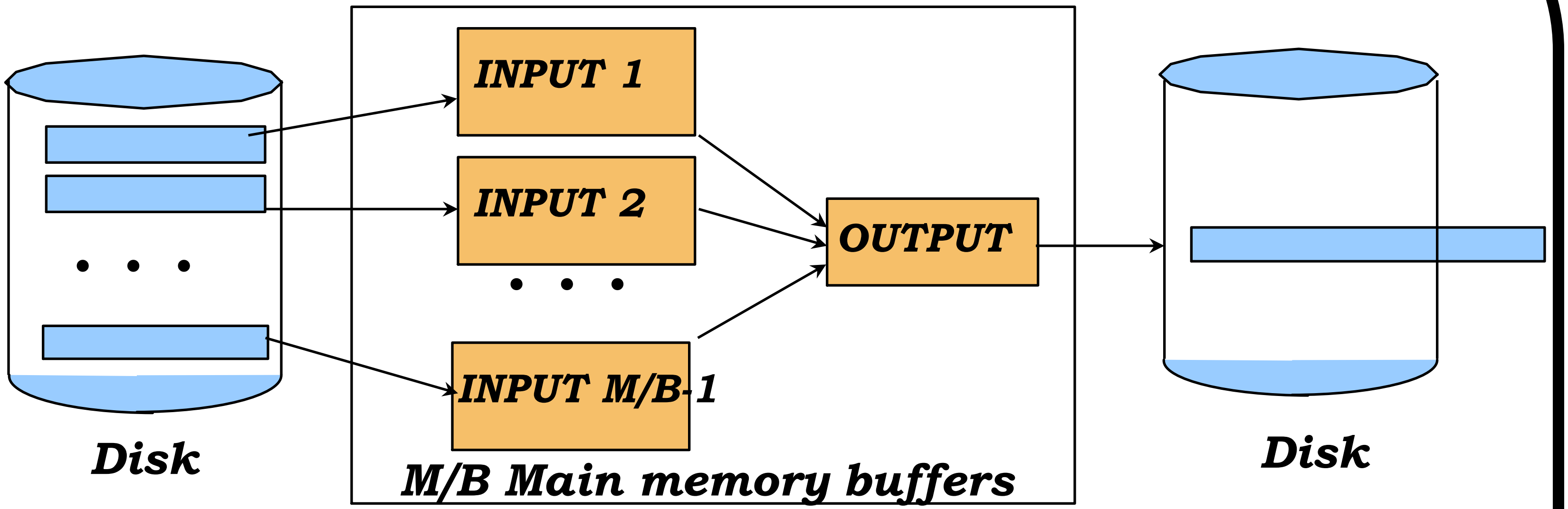
-→ *Two main ideas !*

Phase 1 : Prepare



- *Construct as large as possible starter lists.*

Phase 2 : Merge

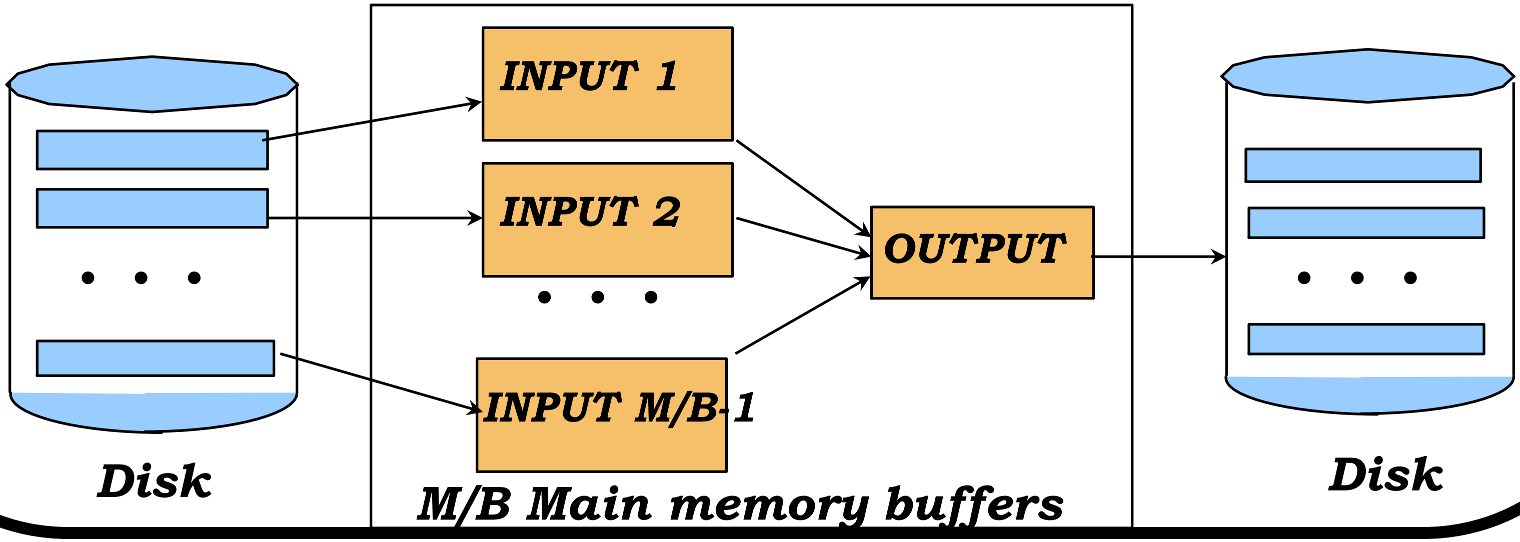


Compose as many sorted sublists into one long sorted list.

General External Merge Sort

** How can we utilize more than 3 buffer pages?*

- To sort a file with *N/B* pages using M/*B* buffer pages:
  - Pass 0: use M/*B* buffer pages. Produce $\lceil N / B \rceil$ sorted runs of *M/B* pages each.
  - Pass 1, 2, …, etc.: merge M/*B-1* runs.



Selection Algorithm

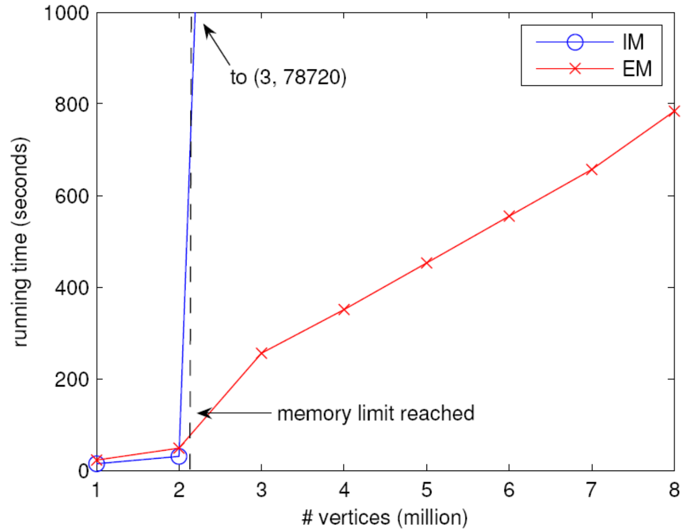
- In internal memory (deterministic) quicksort split element (median) found using linear time selection

- Selection algorithm: Finding *i*'th element in sorted order
  1) Select median of every group of *5* elements
  2) Recursively select median of ~ *N/5* selected elements
  3) Distribute elements into two lists using computed median
  4) Recursively select in one of two lists
- Analysis:
  - Step 1 and 3 performed in $O(N/B)$ I/Os.
  - Step 4 recursion on at most $\sim\frac{7}{10}N$ elements

$\Rightarrow T(N) = O(N/B) + T(N/5) + T(7N/10) = O(N/B)$ I/Os

Toy Experiment: Permuting

- Problem:
  - Input: N elements out of order: 6, 7, 1, 3, 2, 5, 10, 9, 4, 8
    - Each element knows its correct position
  - Output: Store them on disk in the right order
- Internal memory solution:
  - Just scan the original sequence and move every element in the right place!
  - O(N) time, O(N) I/Os
- External memory solution:
  - Use sorting
  - O(N log N) time, $O(\frac{N}{B}\log_{M/B}\frac{N}{B})$



Takeaways

- Need to be very careful when your program's space usage exceeds physical memory size
- If program mostly makes highly localized accesses
  - Let the OS handle it automatically
- If program makes many non-localized accesses
  - Need I/O-efficient techniques
- Three common techniques (recall the majority counting puzzle):
  - Convert to sort + scan
  - Divide-and-conquer
  - Other tricks